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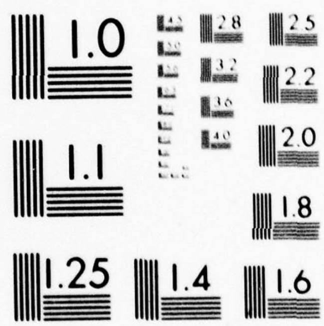

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FURTHER OBSERVATIONS ON TRANSITION IN A PIPE

by

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ABSTRACT

Fully developed Poiseuille flow in a pipe was artificially disturbed at $x/D = 400$ and $1700<Re<4000$. Puffs and slugs generated by the disturbance were identical to the structures observed when the flow in the inlet region undergone transition (Wygnanski and Champagne 1973). Since the disturbance was sufficiently strong to cause transition even at low Reynolds number s the appearance of either puff s or slugs depended on the Reynolds number only. Velocity measurements in the pipe were taken with rakes of hot wires using digital acquisition methods and in this way each realization could be observed in its entirety. The coherence of the large structures was studied in radial and azimuthal directions. Puffs and slugs generated by the disturbance were mapped and found to be identical to the structures observed at the inlet region of the pipe. It was established that a slug which has all the attributes to a fully developed turbulent pipe flow is generated by a coalescence of puffs. The puff, which seems to contain a small number of toroidal eddies appears to be a fundamental coherent structure in a fully developed turbulent pipe flow. Previous observations, which were based on a single-point measurement and ensemble-averaged data did not reveal the full structure of the puff in the same detail as the present techniques. Single realizations were analysed showing instantaneous velocity profiles, vorticity perturbation contours, as well as streamlines moving with the structure. Artificially generated succession of puffs which were allowed to interact, closely resembled a slug. The evolution of a slug from puffs was thus established.

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INTRODUCTION

Recent experiments in turbulent shear flows indicate that the large coherent structures observed might sometimes have their origin traced to the transition region. Two examples may readily be given:

1. A portion of a transitional spot survives in a fully developed turbulent boundary layer for a long time, during which it travels more than a hundred boundary layer thicknesses downstream.

2. A quasi two-dimensional vortex generated at the initiation of mixing maintains its identity in a plane mixing layer.

Thus the understanding of the transition process and and ensuing large turbulent structures may be of vital importance to the understanding of turbulent shear flows.

Fully developed turbulent pipe flow, which is so similar to a turbulent boundary layer developes from turbulent structures occurring during transition. Natural transition in a pipe is dominated by the quality of the flow at the inlet. In a carefully designed inlet, transition occurs at Re $>10^4$ with laminar flow being observed even at Re$=10^5$. When the flow entering the pipe is turbulent and the Re < 2000 the turbulence will slowly decay, when the $Re > 2000$ new puff-like coherent structures are formed in spite of the existence of background turbulence, (Champagne and Helland 1978) and presumably sufficiently far downstream the original turbulence entering the pipe decays entirely while new turbulence characteristic to the pipe has developed. At $2000 < Re < 2600$ the flow in a smooth straight pipe is only intermittently turbulent even when it is fully turbulent at the inlet. The turbulent structures observed are referred to a s puffs and were mapped in detail by Wygnanski, Sokolov and Friedman (1975). The equilibrium puff is a comparatively well defined structure in statistical terms and it maybe a basic building block in a fully developed turbulent pipe flow.

Reducing of the level of the disturbances at the inlet while keeping the Reynolds number constant, results in the disappearance of the puffs and a return to laminar flow. At $Re > 2600$ transition again occurres but it seems to originate differently. Perturbations appear in the accelerating boundary layers associated with the inlet region and grow until the entire cross section of the pipe becomes turbulent. Whenever the flow in the pipe was only intermittently turbulent the structures observed were referred to as slugs . The length of the slug is comparable to the length of the pipe and the structure of flow in its interior resembles fully developed turbulent pipe flow. Consequently, a slug is a much more complex entity than a puff.

Since the early experiments of Reynolds (1883) the investigation of natural transition in a pipe was mostly related to the inlet region which is not as easily defined as the fully developed flow downstream. The attainment of a fully developed, laminar pipe flow even at moderately low Reynolds numbers is rather difficult because the length of the inlet region is proportional to on the Reynolds number. The purpose of the present experiment is to perturb a fully developed laminar pipe flow and observe the ensuing turbulent structures. It was hoped that experiment will reveal the constitution of a large eddy generated in fully dveloped pipe-flow and establish the possible relationship between slugs and puffs. It was conjectured that slugs might have been created by an amalgamation of puffs after they split, grew, and joined again together; but the actual proof of the process was lacking.

APPARATUS AND INSTRUMENTATION

The basic flow apparatus was described in an earlier work. The disturbance was generated by small jets emanating from two sources diametrically opposing one another and having a diameter of 2 mm each. The nozzles are located at $x/D = 400$ where x is the distance from the inlet, and D is the diameter of the pipe. In absence of the disturbance the profile is parabolic for Re < 5000. This roughly agrees with the Atkinson Goldstein criterion which requires that the parameter x/D Re > .08 in order that the flow will become independent of the downstream distance . The jets were produced by a loudspeaker activated by a clipped sawtooth signal. The leading edge of the signal caused a membrane of the speaker to contract rapidly and produce the jets; the trailing edge of the signal caused the membrane to withdraw slowly to its original position. The flow disturbance, near the jets was initially monitored and and found to consist of a large single velocity spike followed by small amplitude, decaying oscillations not exceeding 10% of the amplitude of the spike.

The streamwise velocity component was measured with a rake consisting of 9 hot wire probes positioned radially between the centerline of the pipe and the wall. All rake measurements were made at the exit plane of the pipe 500 diameters downstream of the inlet and 100 diameters from the distubance.

The wires were evenly spaced with wire No. 1 , half a millimeter away from the surface and wire No. 9, on the center-line . The array of sensors permits the measurement of an instantaneous velocity profile across the pipe, and a partial reconstruction of the flow field in its entirety rather than in a statistical sense. The signal from each wire was processed digitally by transmitting it via a 12 bit analog to a digital converter to a mini computer. The data was sampled at the rate of 4000 points per second per wire and was recorded on a digital tape for further processing. The sampling rate was more than adequate since all turbulent fluctuations were found to have negligible energy at frequencies higher than 1000 Hz. Each data record consisted of 9 channels sampled 4600 times, for a total size of 41 400 16 bit words. The tape records served to reanalyse the experimental results using conventional statistical techniques.

RESULTS

The first observations were aimed at establishing the makeup of the turbulent structure evolving from a momentary disturbance located in a fully developed laminar pipe-flow and relating it to the structures observed by disturbing the flow in the inlet. A record of the streamwise component of velocity obtained by the 9 wire rake is shown in Figure 1a and 1b. The abscissa in this figure is time , rendered dimensionless by using the bulk velocity and the diameter of the pipe. The origin coincides with the trailing interface of the structure on the centerline of the pipe. Provided the interface moves with the bulk velocity as it does in the case of the puff, the abscissa will represent a distance measured from the trailing interface . The ordinate represents a velocity perturbation relative to a parabolic profile . Each trace was recorded by a different sensor in a radial array, thus the numbers on the left-hand-side of Figure 1 indicate the location of the sensor. The traces of the velocity shown were taken at Re = 2200 and are similar to the traces shown by Wygnanski, Sokolov and Friedman (henceforth referred to as WSF) for the equilibrium puff. The velocity history shown in figure 1 b were produced by the same disturbance but at Re = 3500, this velocity history is reminiscent of the slug (see Wygnanski and Champagne 1973). The fact that two different structures result from the same perturbation indicate that they depend critically on Re ynolds number rather than on the details of the perturbation, as long as the latter exceedes a threshold level which is capable of generating turbulence.

Although the velocity histories shown in Figure 1a, are reminiscent of those observed in a puff, detailed comparison between the two structures can only be made by using statistical methods . Ensemble - averaged time record of the streamwise velocity for different radia l locations is shown in Figure 2a. Two hundred events constitue an ensemble . The trailing interface of every event as detected by wire No.9, (located on the centre line of the pipe) was aligned by shifting an entire velocity record along the time axis, implicitly assuming that the trailing interface has an identical shape for all realizations and the jitter in the time of arrival of the interface at the measuring station results from variations in the velocity at which the structure is convected . Repeating the process on the same two-hundred events but aligning the data on the basis of the information gathered from wire No. 3, located at $r/R = 0.72$ - yielded somewhat different results (Figure2b). The velocity records shown in Figure 2a exhibit strong accelarations near the turbulent - non-turbulent interface in the central region of the pipe while the records shown in Figure 2b do so closer to the surface . The smearing of the data results from the fact that the shape of the interface varies from one realization to another and the alignment procedure accentuates the flow features in the vicinity of the reference probe. However, the ensemble - averaged velocity record for wire No. 9, in Figure 2a and for wire No. 3 in Figure 2b are essentially identical to the corresponding records presented by WFS. It was concluded that the turbulent structure resulting from disturbing the fully developed Poiseuille flow at Re = 2200 is no different from the structure resulting by disturbing the inlet flow. Assuming that the flow is axisymmetric , and the puff is in a state of equilibrium a streamline pattern in a frame of reference moving with the trailing interface was calculated (Figure 3a). The data from fig.2a was chosen for this purpose and in spite of the fact that WSF alinged their data at each measuring station, shape of the streamlines obtained is similar to the pattern shown in Figure 10 of WSF. It appears that the ensemble-averaged flow pattern in a frame of reference moving with the puff is not very sensitive to the alignment technique although some information must have been lost by the averaging process . The individual ralization contains more eddies than shown in Figure 3a., because the two larger regions of recirculation result from the fact that the puff is embedded in a laminar flow. One can also compute the perturbation of vorticity relative to the laminar flow from the data shown in Figure 2a. This is done by assuming that u/ r is much larger than v/x where v is the radial component of velocity and x being the distance in the streamwise direction. Positive numbers in Figure 3b, imply that the vorticity in the laminar flow exceeds the vorticity in the puff while negative numbers imply the opposite. We thus see that the appearance of turbulence is associated with the transport of vorticity towards the surface of the pipe. The small insert in the left-hand corner of Figure 3b shows schematically the laminar and turbulent velocity profile associated with transition in a pipe. The shaded region in this insert indicates the radial location corresponding to positivie perturbation contours of vorticity. The strongest perturbation in vorticity corresponds in time to the concentrated shear area near the trailing edge of the puff and thus is related to the single toroidal eddy observed by the WSF. Obviously, the center of the rotating stream lines does not correspond to the contours of maximum vorticity perturbation (see also Hama 1962), nor does it correspond to the maximum turbulent intensy (WSF).

In order to establish the similarity between puffs and slugs at similar Reynolds numbers the flow was disturbed at Re = 2600 and the resulting perturbation in velocity was again sampled and ensemble averaged . Results shown in Figure 4a were obtained by aligning wire No. 9, in the same manner as it was done in Figure 2a, . The velocity perturbation near the trailing edge of the slug is very similar to the velocity perturbation near the interface of a puff , in fact the flow overtaking the interface deccelerates very rapidly and then accelerates again producing a local spike in the ensemble average velocity record . The velocity then remains constant over most of the duration of the slug slowly accelerating near the leading edge in order to attain the laminar velocity prevailing in the central region of the pipe . It is suggested that the velocity perturbation near the trailing, and leading edges of the slug is also similar to the velocity perturbation in the puff . The cenral region of the slug is different and could possibly result from a train of puffs which merged together. The constancy of velocity in this region maybe due to the ensembling process which smears the detailed structure with in the turbulent region. The streamline pattern calculated for the data shown in Figure 4a, with respect to the bulk velocity is shown in Figure 4b. It should be stressed however, that the bulk velocity in this case does not have the same meaning as with the puff where it also represents the velocity at which the trailing interface of the puff is convected downstream. In this case the trailing interface of the slug moves somewhat slower while the leading portion of the slug moves a faster than the bulk velocity , the differences however, are not large because of the similarity of Reynolds numbers at which the measurements were taken. By removing the central portion of the streamline pattern and patching the patterns near the trailing and leading interfaces of the slug one obtains a flow field which is very similar to the flow field in an ensemble-averaged puff. This is another indication that the puffs and the slugs in transitional pipe flow are related .

After establishing that the interface region of a slug resembles the structure of the ensemble averaged puff we shall endeavour to explain the mechanism by which slugs can be generated when fully developed Poiseuille flow had been disturbed at Re > 2600. WSF observed that a single disturbance of short duration when applied at the inlet of the pipe resulted in a single turbulent structure when Re was either less than 2300 or more than 2800. In the range 2300 < Re < 2800 a single pulse applied to the flow at the inlet could result in a number of puff like structures further downstream. At x/D = 500 the average number of puffs seen at Re=2600 was about 4, and their length was not identical. Although some individual puffs were observed to grow, their rate of growth was too small to cause genuine transition to turbulence; splitting of individual puffs , followed by growth and recombination was conjectured to be the predominant mechanism of transition. We should first endeavour to show that recombination of puffs gives rise to the larger slug-like structure . The ensemble-averaged velocity records, streamlines , and vorticity perturbation shown in Figure 5, were obtained at x/D = 500 when the fully developed laminar flow was disturbed by a single pulse at x/D = 400 at Re = 2550. Observing the individual realizations on an oscilloscope suggested that splitting have occurred , but since the distance between the location of the disturbance and the measuring station was only 100 diam. multiple splitting of puffs was rather rare; only two puffs in tandem were most frequently observed. The results shown in Figure 5, represent 200 consecutive events without any preselection or classification . Naturally the splitting mechanism which is not controlled by the initial perturbation does not occur at the same time and location in the pipe causing the leading puff to be smeared by the averaging process . One could refine the averaging by correlating each individual realization with the pattern shown in Figure 5a and reclassify some of the events, but a much simpler method showing the coalescence of puffs into a slug was found. Reducing the Reynolds number to 2200 (just prior to the occurrence of the natural splitting) two consecutive perturbations were introduced into the flow ; the time interval, t, between the perturbations could easily be adjusted providing various degrees of interference between adjacent puffs. At long time intervals two individual puffs were observed, when t was reduced to 610 msec the structures started to interact at the measuring station . The first puff in the train appeared to be shorter , and the velocity in the central region of the pipe did not always recover to its unperturbed value. By determining the location of the trailing interface of the second puff and ensembling 200 events together the resulting streamlines and vorticity perturbations still maintain some of the character of the individual puff (Figure 6) . However , the perturbation of the flow near the leading structure is weaker than near the second stucture in the train. Shortening the time interval between the disturbances to 320msec., at the same Reynolds number causes stronger interaction, between the adjacent structures (Figure 7). In fact, the trailing edge of the first puff is no longer clearly distinguishable in most individual realizations, let alone in the ensemble shown in Figure 7. The ensemble averaged velocity history shown in Figure 7a are already resembling the results obtained for a slug (Figure 4a) . There is however very strong resemblance between the results shown in Figure 7 and the results shown in Figure 5, for the naturally split puff. The similarity applies also to streamlines and vorticity perturbation contours . It is obvious that the mean flow at the border between the two turbulent structures no longer recovers to its laminar value.

Shortening the time interval between the adjacent disturbances below 200 msec results in the appearance of a single puff 100 diameters downstream from the perturbation. In this respect the interacting puffs are similar to the array of transitional spots in a boundary layer which give rise to the universal, logarithmic velocity profile, after they are allowed to interact for sufficiently long time. We may conclude then that the merging of puffs results in the generation of slugs whenever transition occurs in the fully developed Poiseuille flow

An independent verification suggesting that the slug is no more than a train of puffs after they merged together can be obtained by measuring the length of the slug . Since we have no control over the splitting and merging process the variation in the length of the slug depends on the number of puffs in the train. Since the length of the puff corresponds roughly to 25 diameters, before it is strongly interacted with other puffs in its vicinity, the length of slugs should roughly vary by quantum jumps of 25 diameters. A histogram showing the variation in the length of slugs generated at Re = 10,000 by a single disturbance at x/D = 400 and observed 100 diameters further downstream is shown in figure 8, . In spite of the small number of events , 200 in all the histogram has obviously two peaks which are approximately 25 diameters apart . Thus, it would appear that most slugs contain an integer number of puffs . It should be stressed however that whenever the distance between the origin of the disturbance and the measuring station was much larger or the Reynolds number was lower it was more difficult to observe the quantum jump in the length of the puff. , because the latter contained more puffs in its hold and the ratio between the length of the puff to the length of a slug became less significant.

A more detailed comparison between the structure of the puffs and the slugs, can only be made by examining individual realization s, since too much information is lost by the averaging process The streamline patterns in Figure 9 correspond to the velocity records shown in fig. 1a and b, . Before calculating the streamline s, the velocity records were filtered in order to eliminate some of the high frequency fluctuations, and observe more clearly the large scale eddies in the flow. The streamline s were calculated assuming that the flow is axisymmetric at every instant , this is much too restrictive an assumption which is not expected to be generally valid. , and its inadequacy reflects itself in a fact that some streamlines shown in fig 9a intersect the wall of the pipe.

This of course is unacceptable on physical grounds and it results from the presence of azimuthal fluctuations. Nevertheless the gross behaviour of the streamlines shown in Figure 9a resembles the shape of the streamline pattern shown in Figure 3a for the ensemble averaged puff . The pattern contains however, much more details which are not hampered by the averaging process , the puff seems to contain two large vortices assumed to be toroidal and extending from the wall to about half the radius . The shear between these vortices is expected to be strong resulting in a vigorous production of turbulence . The puff appears to contain however three or four more eddies which do not produce as strong a perturbation to the flow. Streamlines calculated from Figure 1b and shown in Figure 9b indicate that this particular realization contains four pairs of counter-rotating vortices. Each pair could easily be identified with the region of high turbulent activity within the slug . It is conjectured that each pair of vortices was originally associated with a puff and a number of such puffs merged together to produce the structure observed in Figure 1b. Figure 10a and b , shows the vorticity perturbation contours for these two events. It is obvious that the strongest perturbation in vorticity is associated with the large vortices observed. Although most of the negative vorticity perturbation occurs near the surface of the pipe, the contours of positive perturbation in vorticity correspond roughly to the central core of the vortices shown by the enclosed streamlines.

Instantaneous velocity profiles were cross plotted from the velocity records shown in Figure 1b. Thirty four profiles evenly spaced, and spanning in time the entire slug are shown in Figure 11a, the time span corresponds to the arrow marked at the bottom of Figure 1b. Each profile is compared with the laminar velocity profile existing in the flow in absence of the perturbation in order that the deviation from laminar flow could be easily followed. The first and the last profiles in Figure 11a deviate little from the unperturbed flow. The velocity profiles in the interior of the slug bear at times no resemblance to the long time averaged fully developed turbulent velocity profile. Profiles 9-11;21 22, are fairly flat across most of the cross section of the pipe. The absence of mean shear in the central region of the pipe maybe correlated to the absence of high frequency fluctuations at the particular location in the slug. Some other velocity profiles (notably 12, 15, 20)have their maxima closer to the surface of the pipe than to the center line. Other profiles may have numerous inflection points at various radial locations in the pipe. Expanding the time scale by a factor of 5 starting with profile number 3, the instantaneous velocities near the leading edge of the slug are shown in Figure 11b. Although the time span between adjacent profiles in this figure has been reduced to 8 msec, the rapid changes in the shape of the velocity profile between consecutive realizations was quite surprising. The cause of these changes may be attributed in part to the lack of axial symmetry and strong azimuthal fluctuations. In fact, the shaded areas in Figure 11a, indicating an excess or a defect of velocity relative to the unperturbed laminar flow, are not equal for each and every profile, thus, if one were to calculate the instantaneous mass flow on the basis of these profiles one would conclude that it changes violently. This is of course not the case but simply an indication to the lack of axial symmetry and the differences between adjacent velocity profiles plotteed in Figure 11b maybe due in part to azimuthal flow. The quiesent region downstram of the leading interface is exemplified by velocity profiles which are fairly uniform in the radiad direction over most of the pipe cross section. The variation between adjacent profiles in the lower part of Figure 11b is rather small. It comes then as no surprise that the turbulent activity within a slug is concentrated in bursts of short duration. The behaviour near the trailing edge of the slug is not much different from the behaviour near its leading edge. Furthermore, one may observe a periodicity in the velocity profiles which span the entire duration of the slug and are shown in Figure 11a. This observation is consistent with the idea that the slug contains a limited number of puffs in its hold. The instantaneous velocity profiles in a puff are examined at Re= 1700 in order to reduce the effect of high frequency fluctuations existing at higher Reynolds numbers. The velocity histories shown in Figure 12a were cross plotted for this purpose. In a laboratory frame of reference the approaching puff is marked by decceleration fluid in the central region of the pipe, and the concommitant acceleration at $r/R > 0.6$ (Figure 12b). The velocity profiles in the leading region of the puff resemble the profiles in the quiesant period of the turbulent slug. Only near the trailing edge of the puff strong accelerations can be deduced from the rate at which the velocity profile changes its shape between successive realizations. (Just downstream of the location of the trailing edge of the puff in the central core of the flow the velocity profile contains usually one inflection point at $r/R = 0.8$.)

The velocity profiles shown at the bottom right of Figure 12b can result from a quasi axissymetric eddy moving with the trailing interface. The eddy suddenly breaks down at $r/R = 0.3$ and at a time corresponding to the location of the trailing interface at that radial position. A spike in velocity ensues at $r/R = 0.3$ is in agreement with the location of breakdown in a boundary layer undergoing transition. Another azymuthal eddy seems to be forming near the surface of the pipe after the occurrence of breakdown. Thus, it is quite possible that in a frame of reference moving with the trailing interface of the puff, the eddies are forming near the surface and growing into the central portion of the pipe. An eddy located near the surface of the pipe at the trailing edge of a puff should distort the shape of the trailing edge provided the eddy is contained in the turbulent region of the puff. The shae of the trailing edge of a puff 6 different realizations is shown in Figure 13. The trailing interface sweeps back from the centerline of the pipe, however at an intermediate radial location, most often encountered at $r/R = 0.75$ the direction of the sweep back changes. The variation in the shape of the trailing interface from one realization to another is quite large as maybe observed from Figure 13. and the hump in the profile of the interface may be associated with the location of the large eddy marking the boundary of the turbulent puff. Additional observations of the puff at a low Reynolds number are necessary in order to determine the constitution of the puff more precisely.

A rough assessment of the axial symmetry of each individual realization can be made from the osciloscope traces shown in Figure 14. Four hot-wire sensors located at $r/R = 0.9$ and separated by an azymuthal angle of 90 deg. were placed at the exit plane of the pipe and monitored on an osciloscope. It may be seen that the puff, the slug and the split puff are basically axissymmetric in their structure. There are however many imperfections as the large eddy constituting the puff may be quite corrugated and sometimes even skewed relative to the exit plane of the pipe. The bottom trace in Figure 14 was taken on the centerline in order to show that the other three traces correspond to a puff merging with a slug.

CONCLUSIONS

A strong disturbance applied to a fully developed laminar pipe flow inititates turbulence in the same way as the disturbance in the inlet region of the pipe. The transitional stucture in the pipe depends on their Reynolds number. Puffs are generated at Re< 2200 while slugs occur at Re> 2600. The relationship between puffs and slugs was established as it was shown that the slug consists of a number of puffs which split and merged together to form a larger turbulent structure. The puffs consist of a small number of large eddies which are predominantly axissymmetric in nature.

LIST OF FIGURES

of velocity comprising of 200 events at Re= 3500.

4b. The streamline pattern corresponding to Figure 4a.

5a,b,c. Ensemble averaged record of the streamwise component of velocity, streamlines vorticity perturbation at Re= 2550 (Naturally split puff).

6a,b,c. Ensemble averaged record of the streamwise component of velocity, streamlines vorticity perturbation at Re= 2200(t=0.61 sec).

7a,b,c. Ensemble averaged record of the streamwise component of velocity, streamlines vorticity perturbation at Re= 2200(t=0.32 sec).

8. A histogram showing variation in the length of the slug at Re= 10000.

9a. A streamline pattern in a single puff at Re= 2200.

9b. A streamline pattern in a single slug at Re=3500.

10a. Vorticity perturbation in a single puff at Re= 2200.

10b. Vorticity perturbation in a single slug at Re= 3500.

11~ . Velocity profiles in a slug at Re= 3500(t=40 msec).

11b. Velocity profiles in a slug at Re= 3500(t= 8 msec).

12a. Velocity history in a single puff at Re= 1700.

12b. Velocity profiles in a puff at Re= 1700(t= 20 msec).

13. The shape of the trailing edge at Re= 1700.

14. Simultaneous traces of the streamwise velocity components obtained by 4 hot wire probes located at the same radial position.

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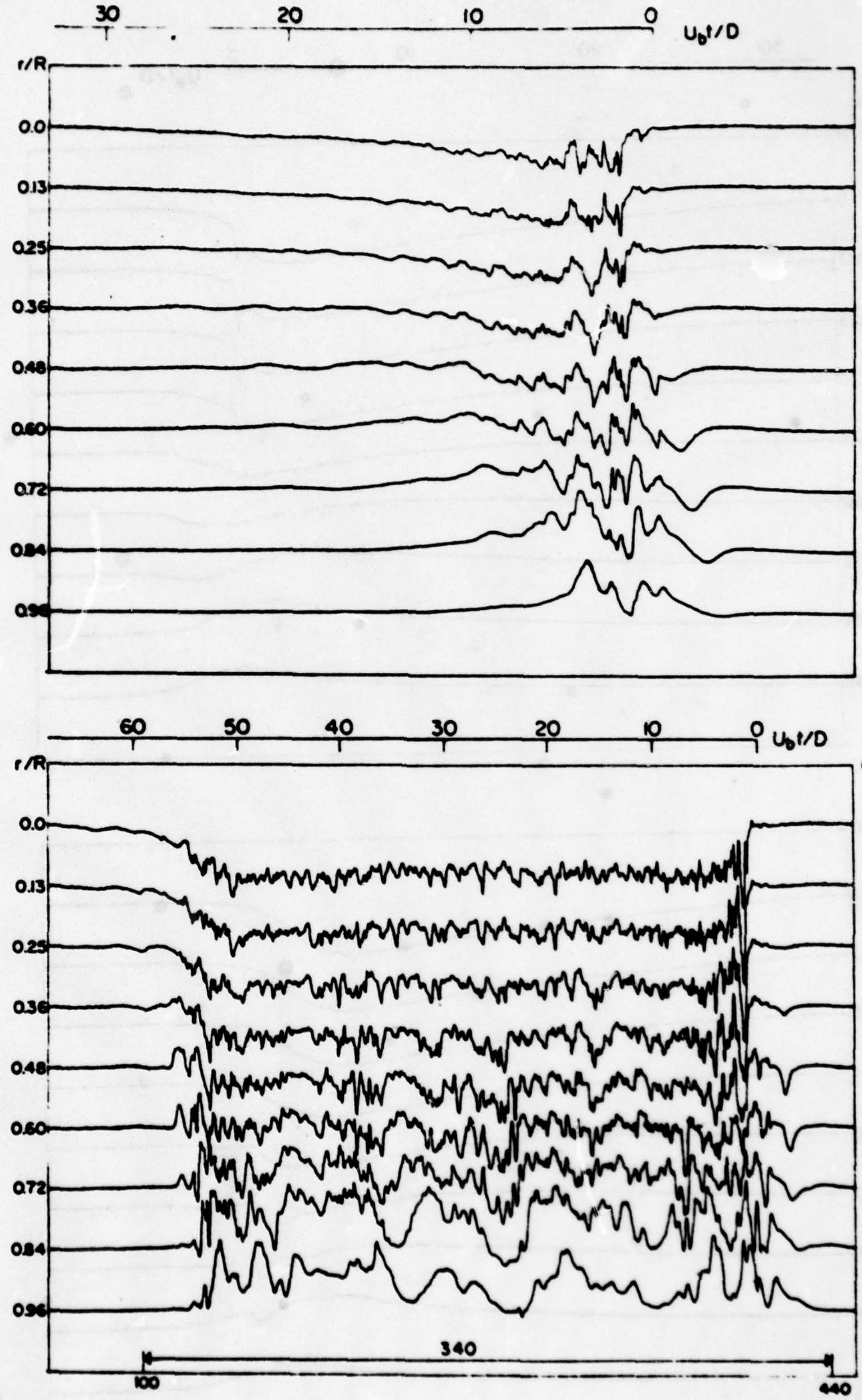

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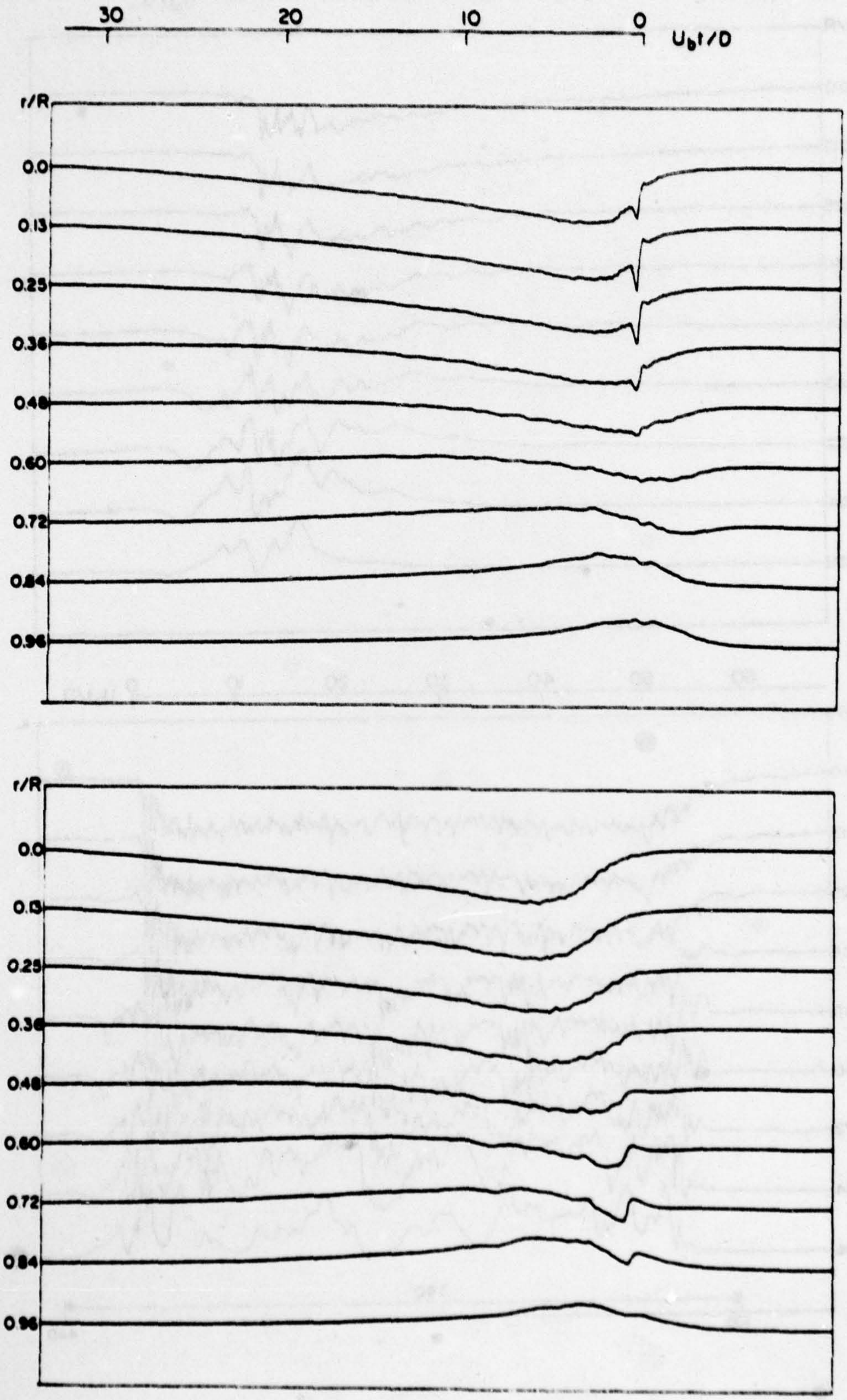
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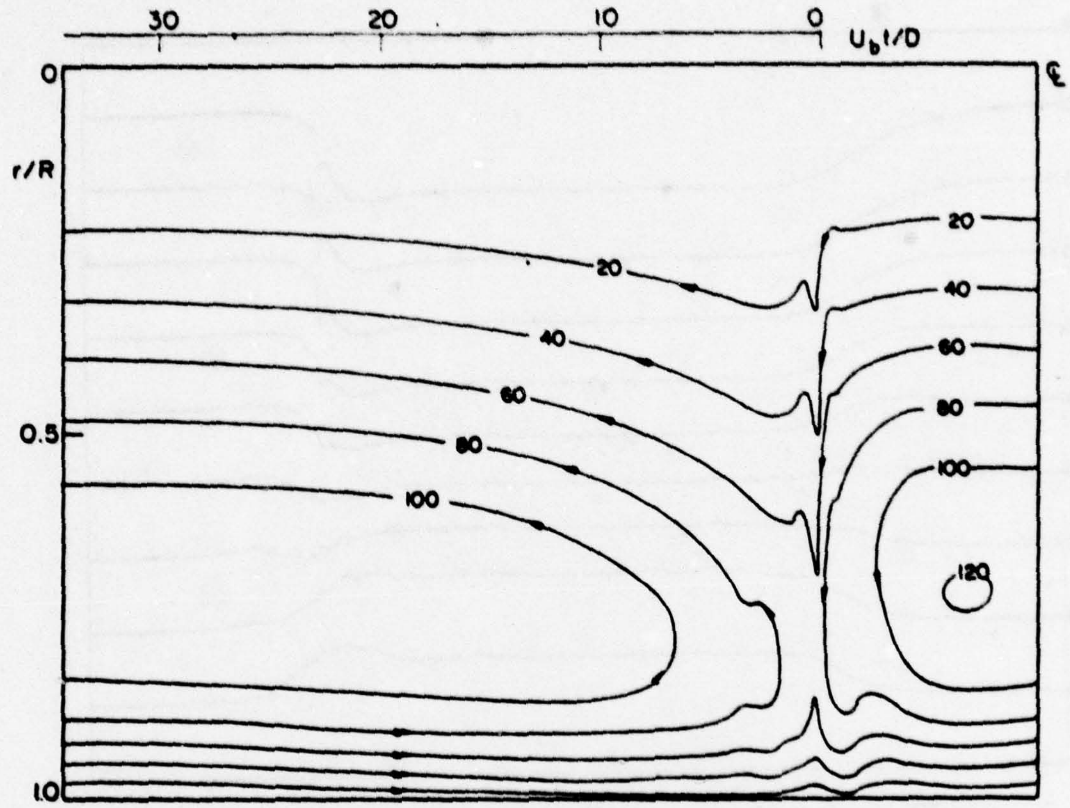
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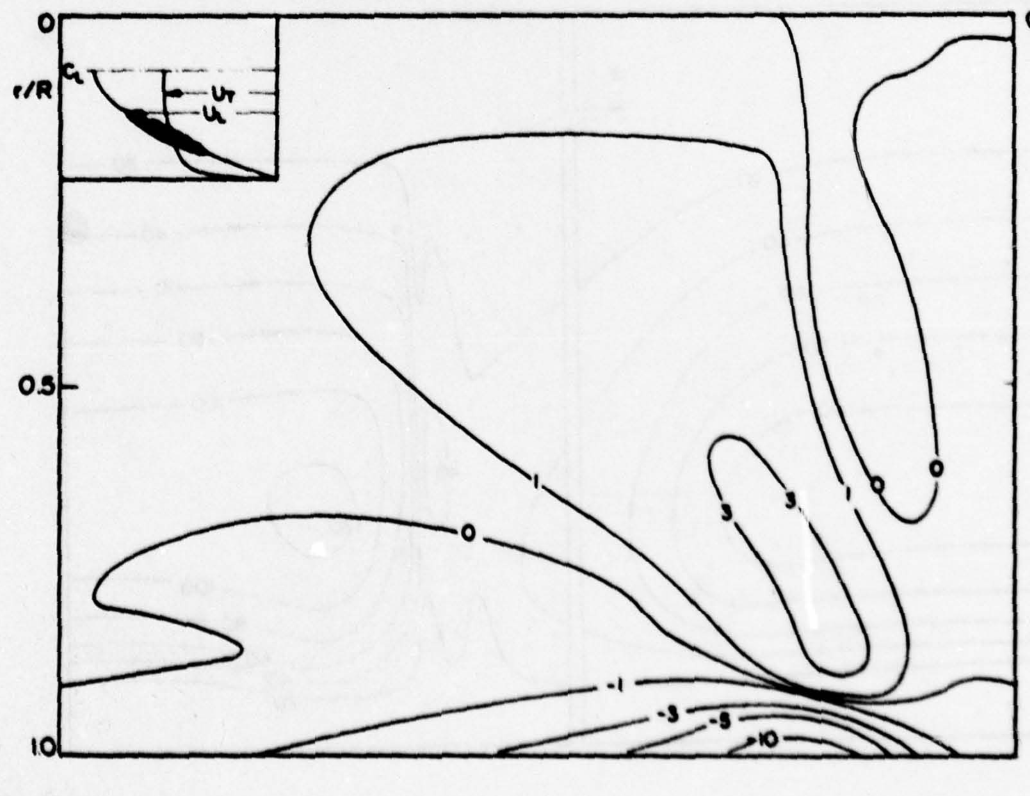
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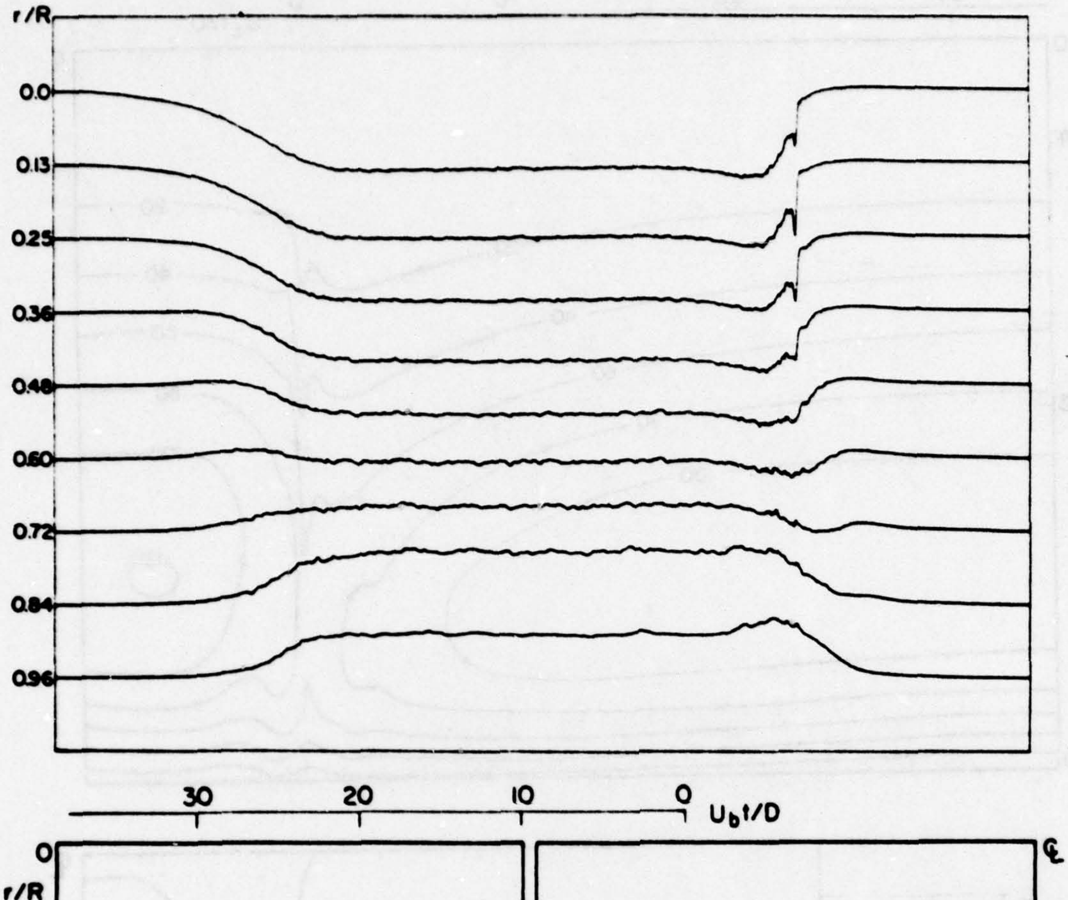

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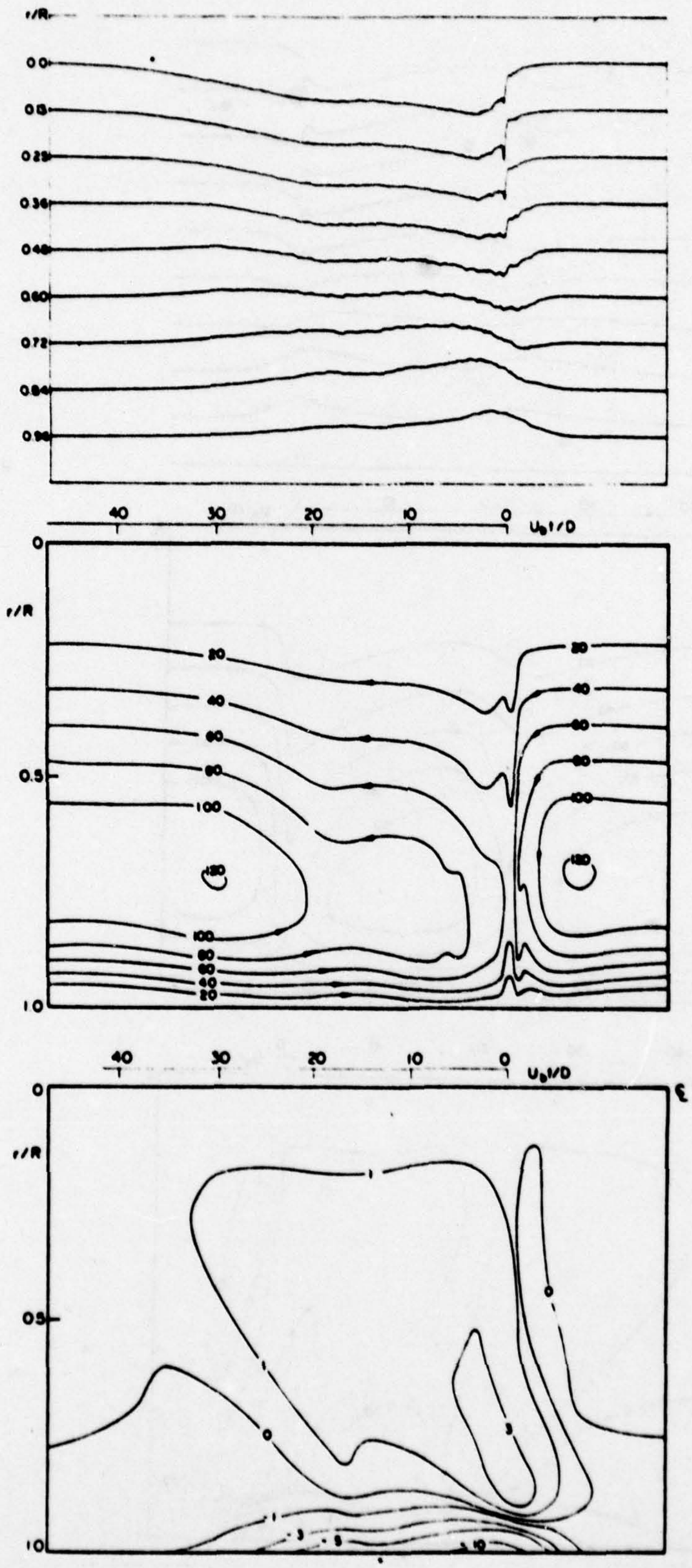
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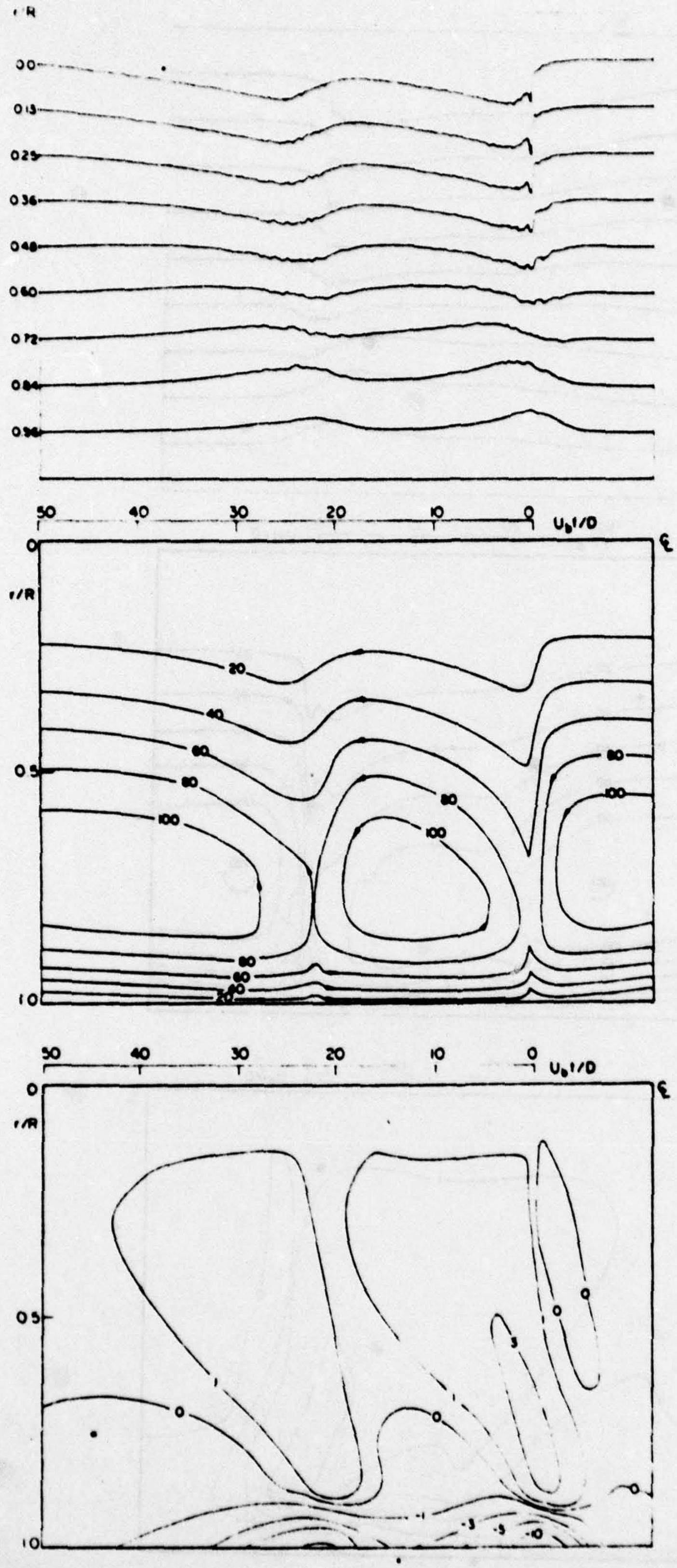
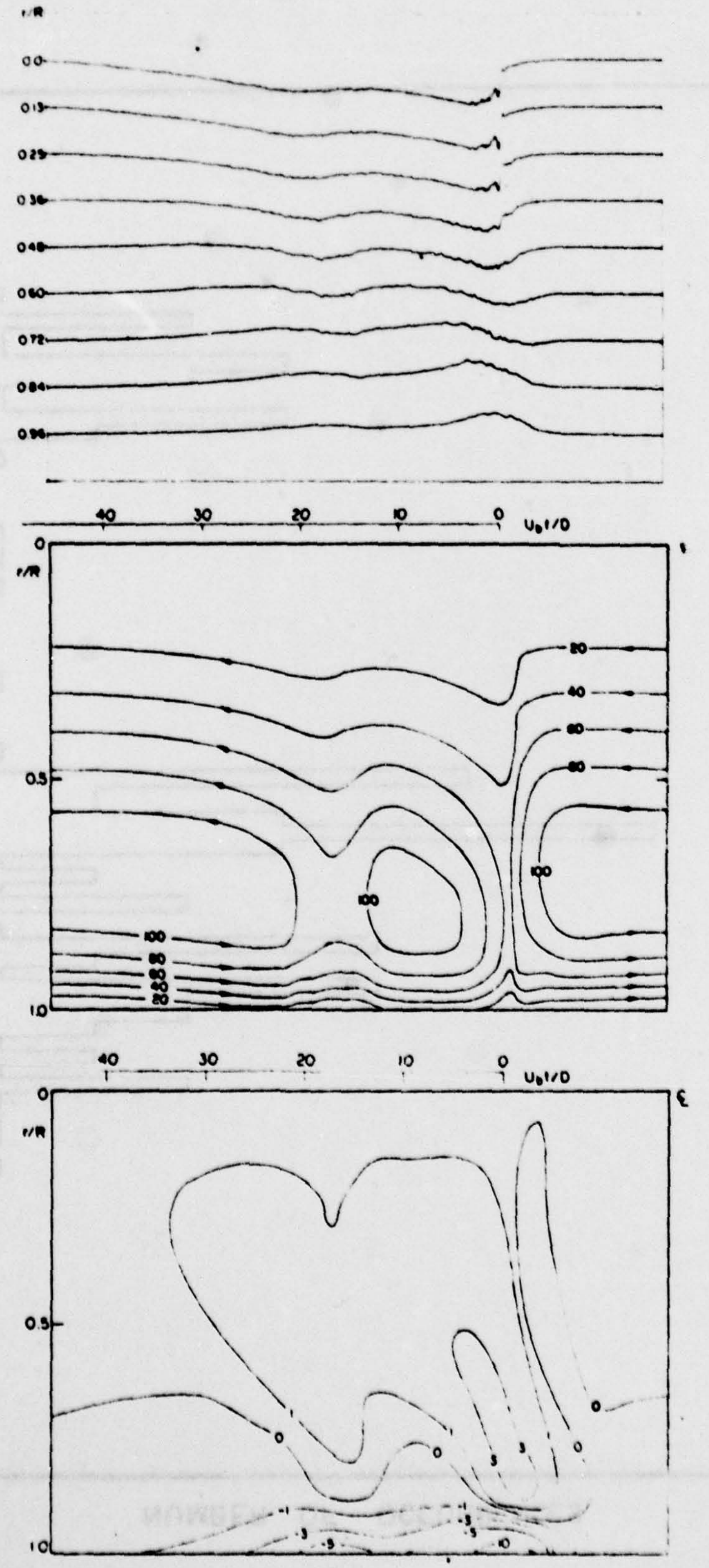
1.0
20
40
60
80
100
120
0
r/R
0.5
1.0
0
1
3
5
10


r/R
0.0
0.13
0.25
0.36
0.48
0.60
0.72
0.84
0.96
50
40
30
20
10
0
$U_b t/D$
℄
20
40
60
80
100
0.5
1.0
0
3
-1
-3
-5
-10


r/R
0.0
0.13
0.25
0.36
0.48
0.60
0.72
0.84
0.96
40
30
20
10
0
$U_b t/D$
0
r/R
0.5
1.0
20
40
60
80
100
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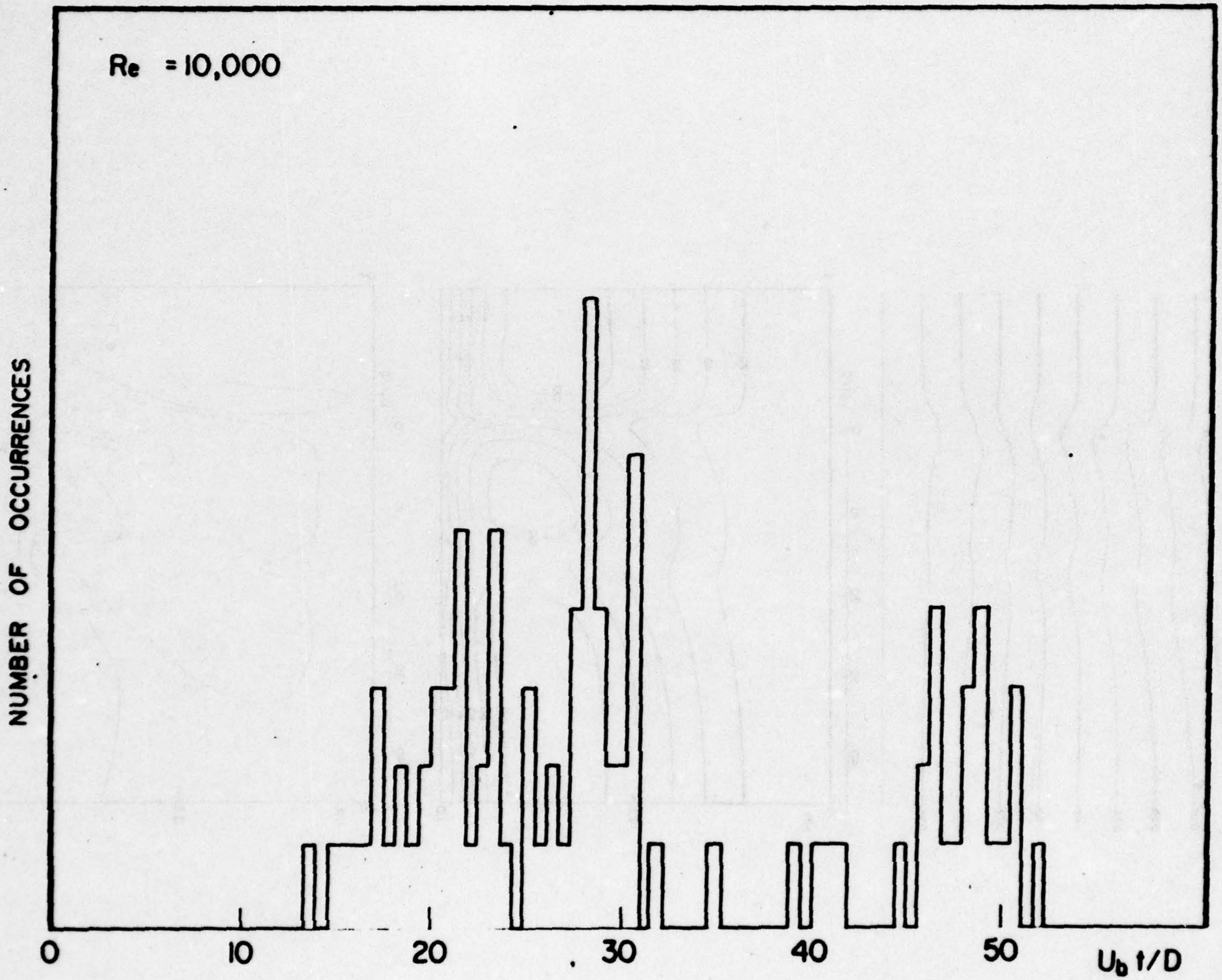

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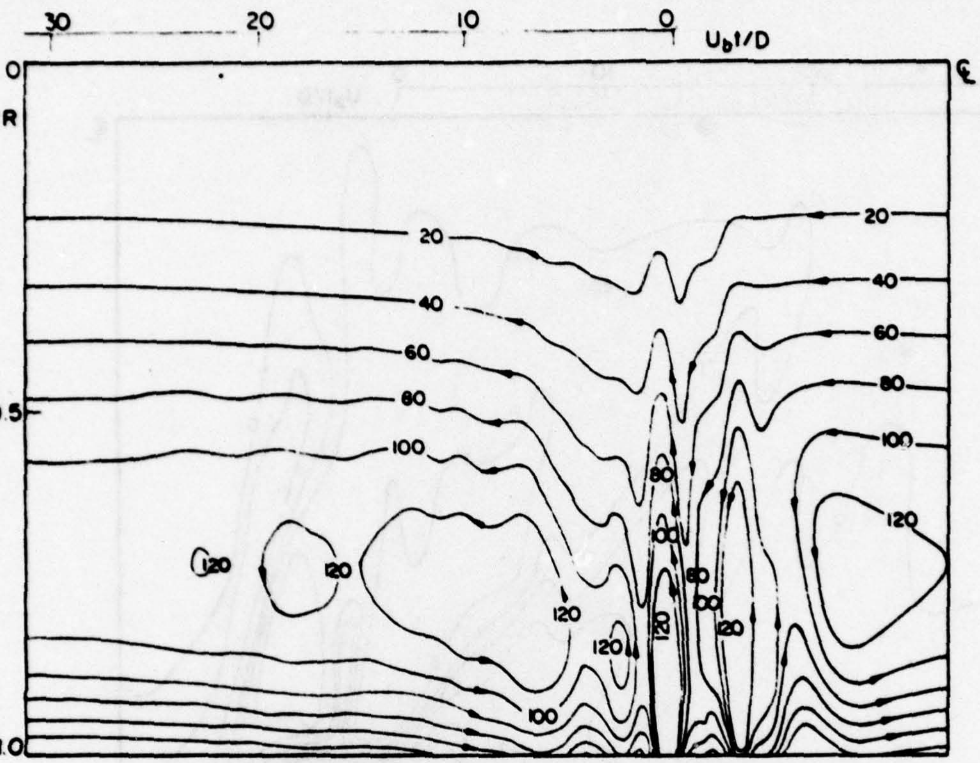

30
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$U_b t/D$
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r/R
0.5
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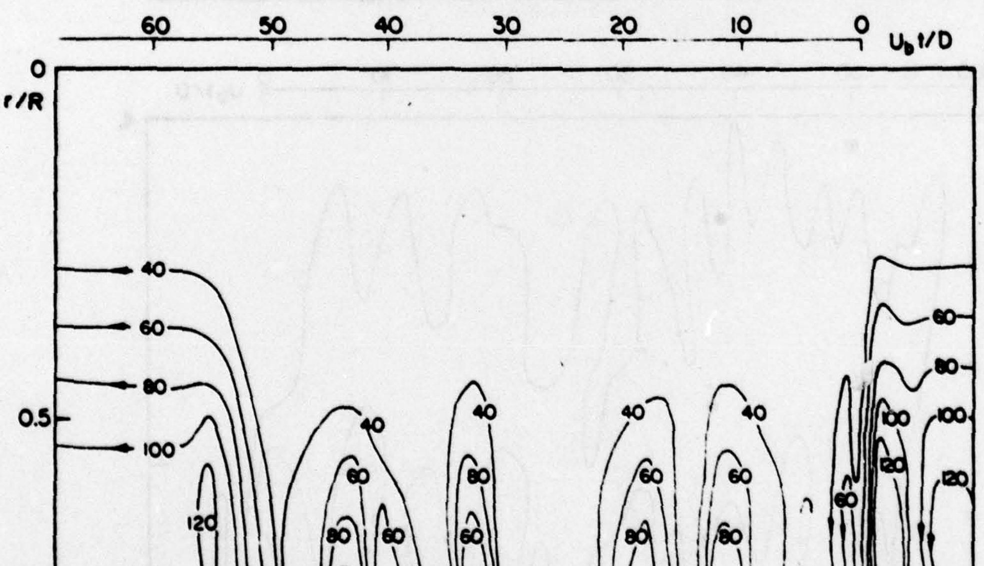
100
120



60
50
40
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$U_b t/D$
0
r/R
0.5
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60
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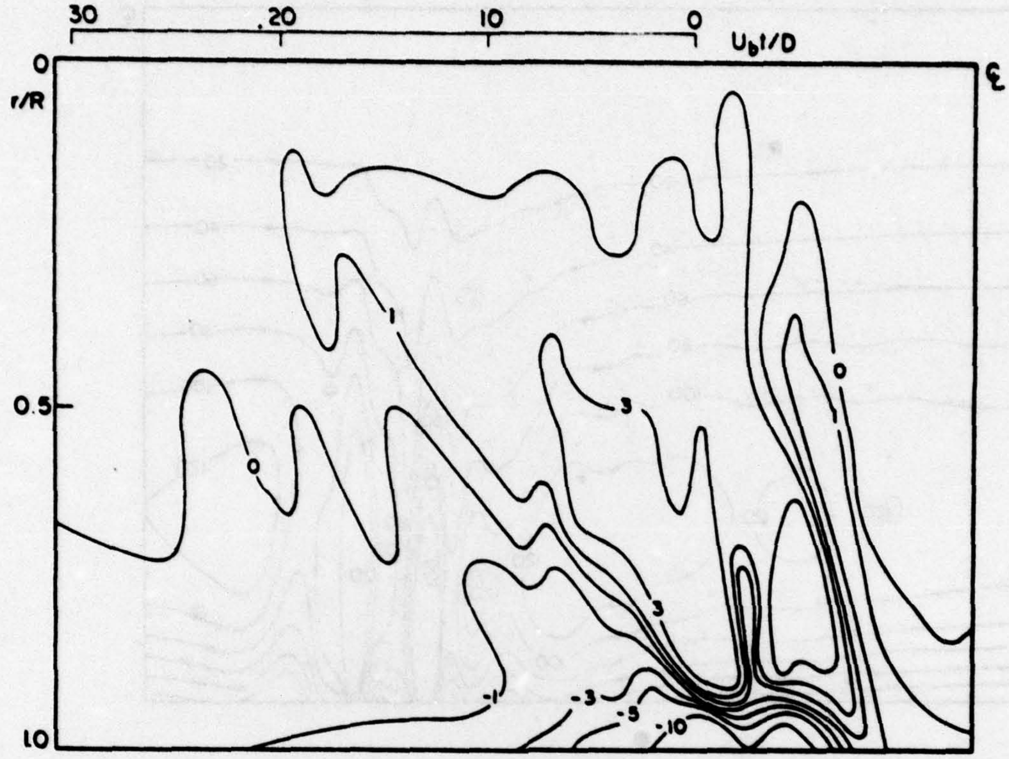
100
120



30
20
10
0
$U_b t/D$
r/R
0
0.5
1.0
℄
0
1
3
-1
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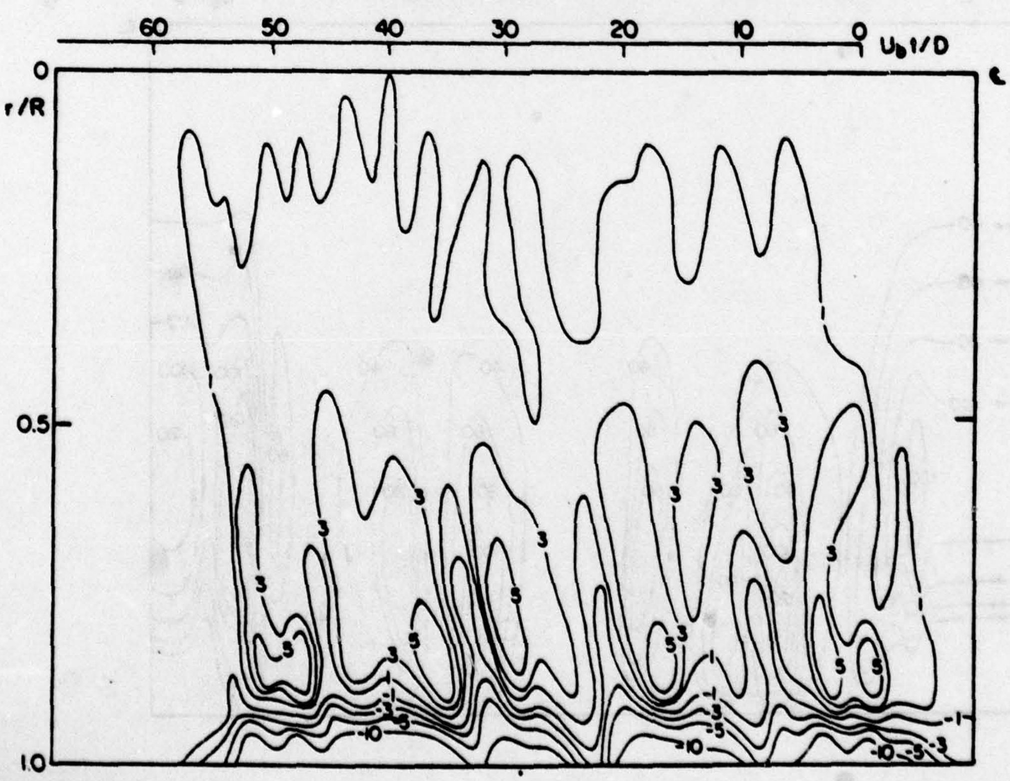
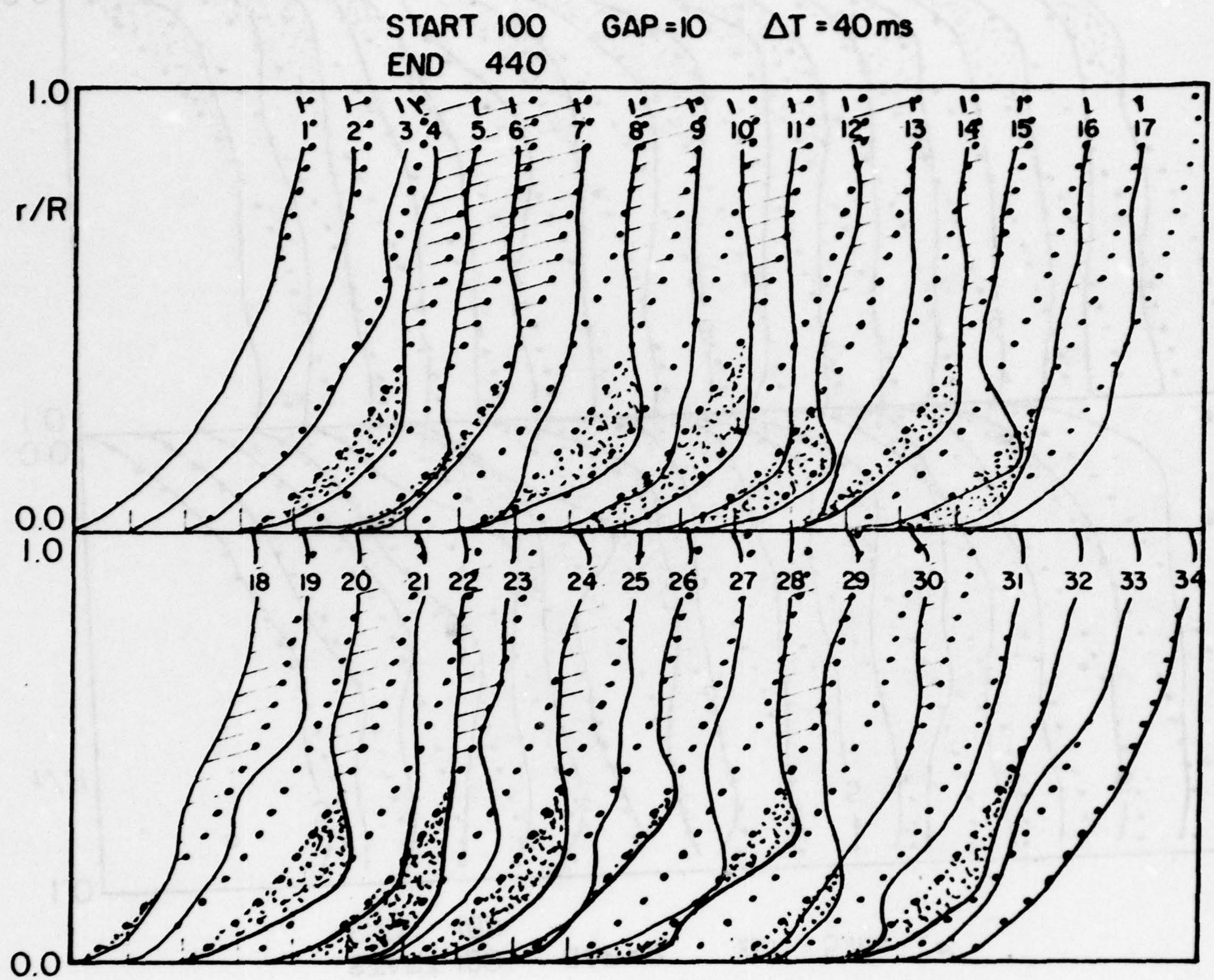
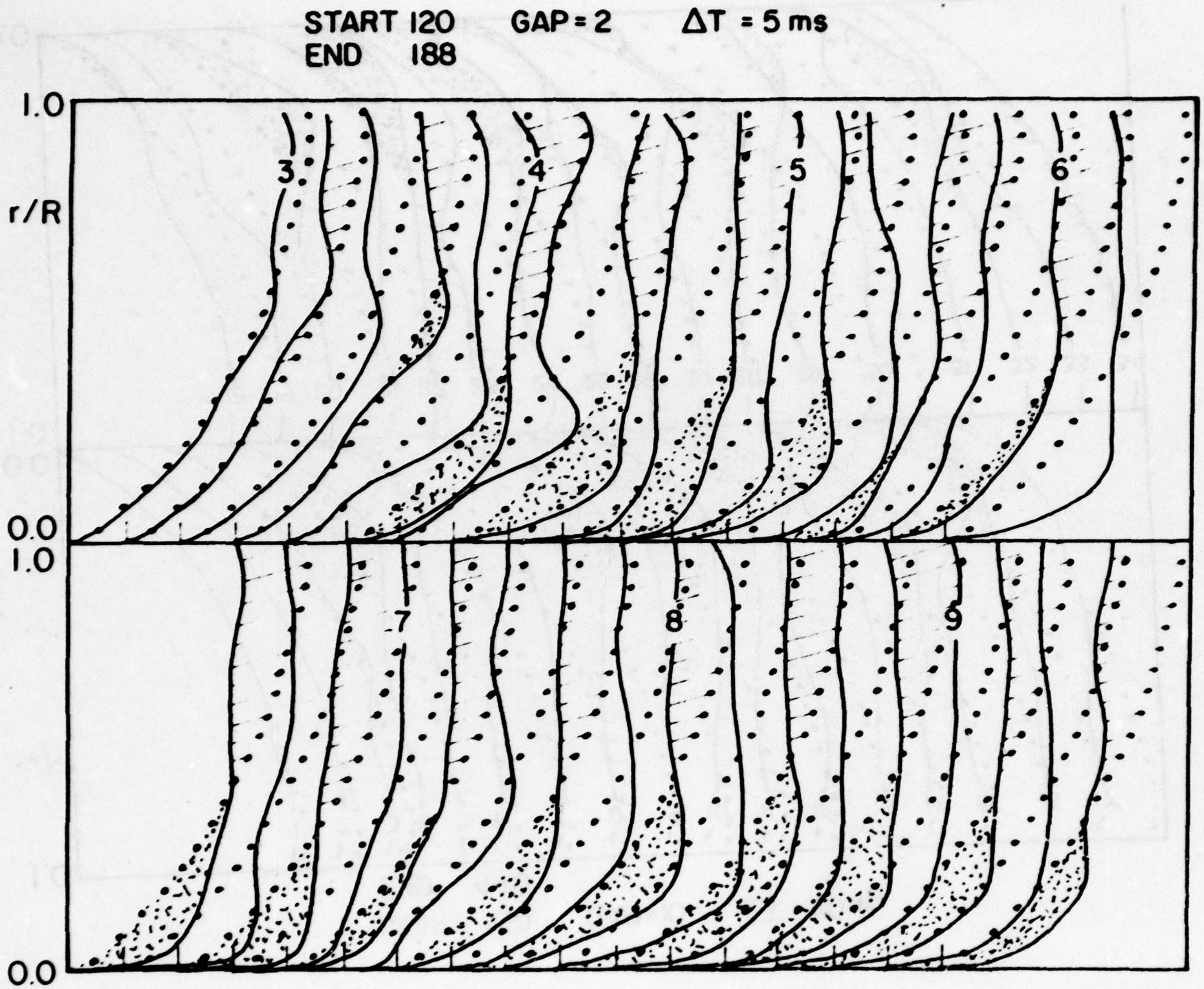
-5
-10

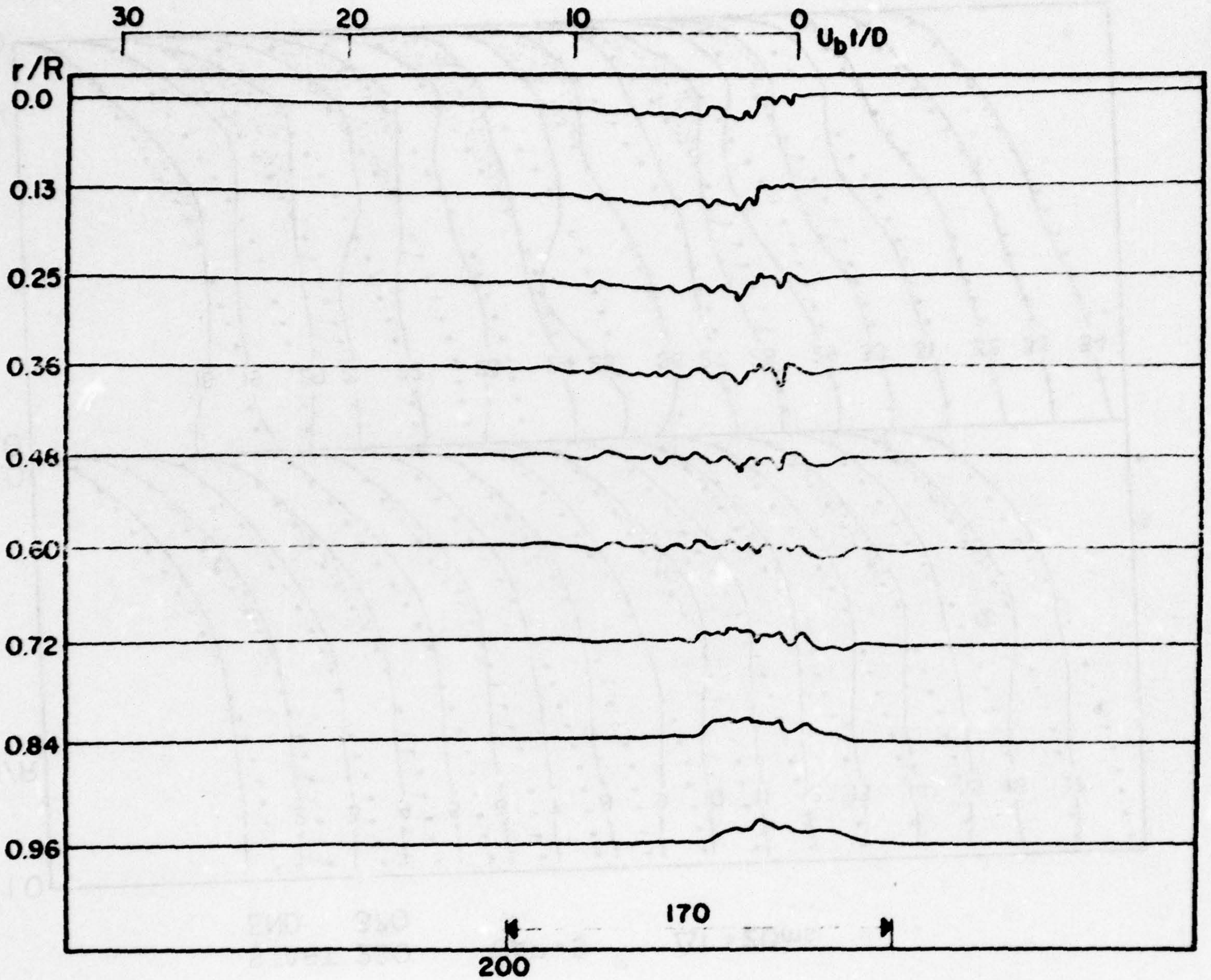


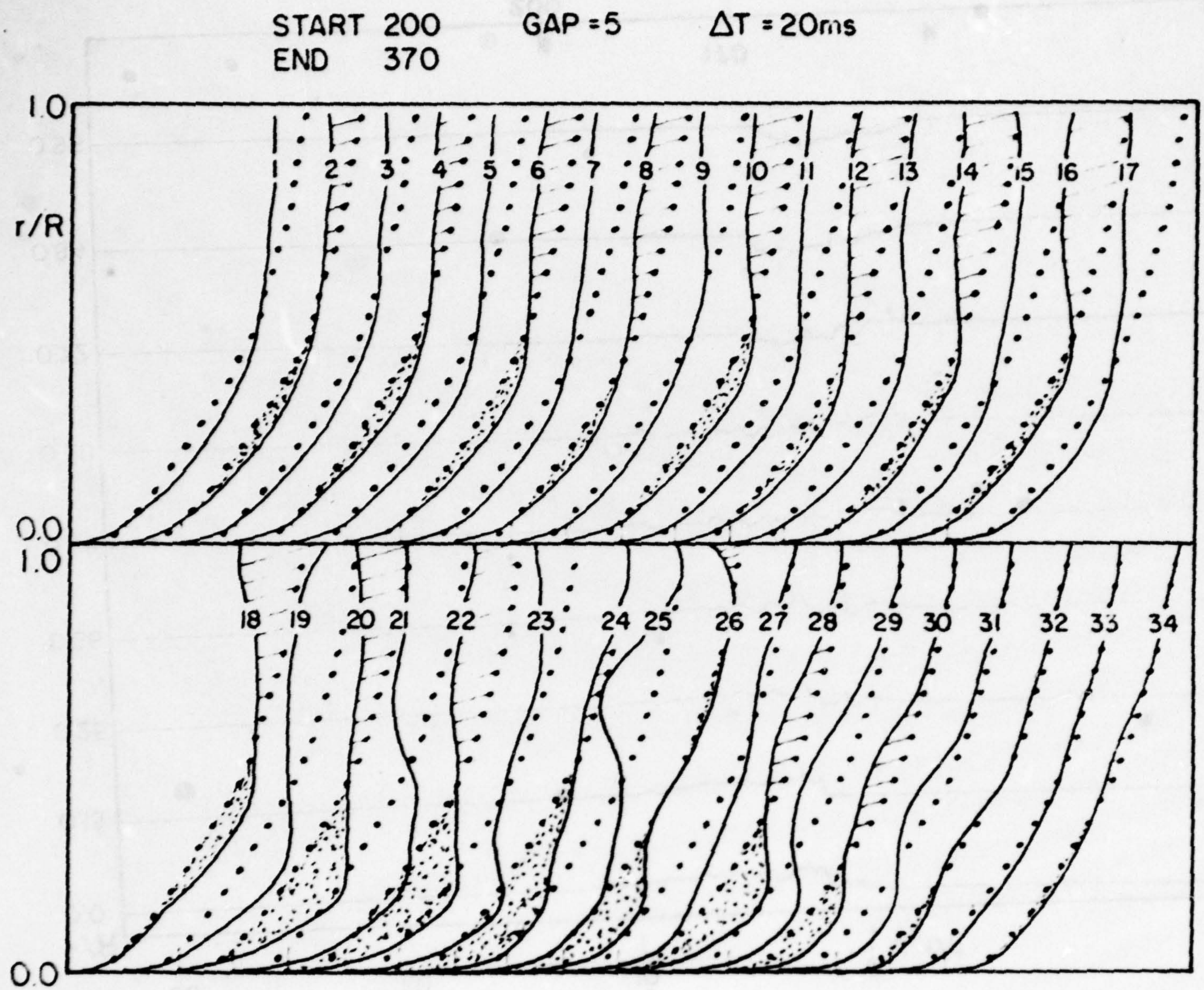
60
50
40
30
20
10
0
$U_b t/D$
r/R
0
0.5
1.0
℄
3
5
-1
-3
-5
-10

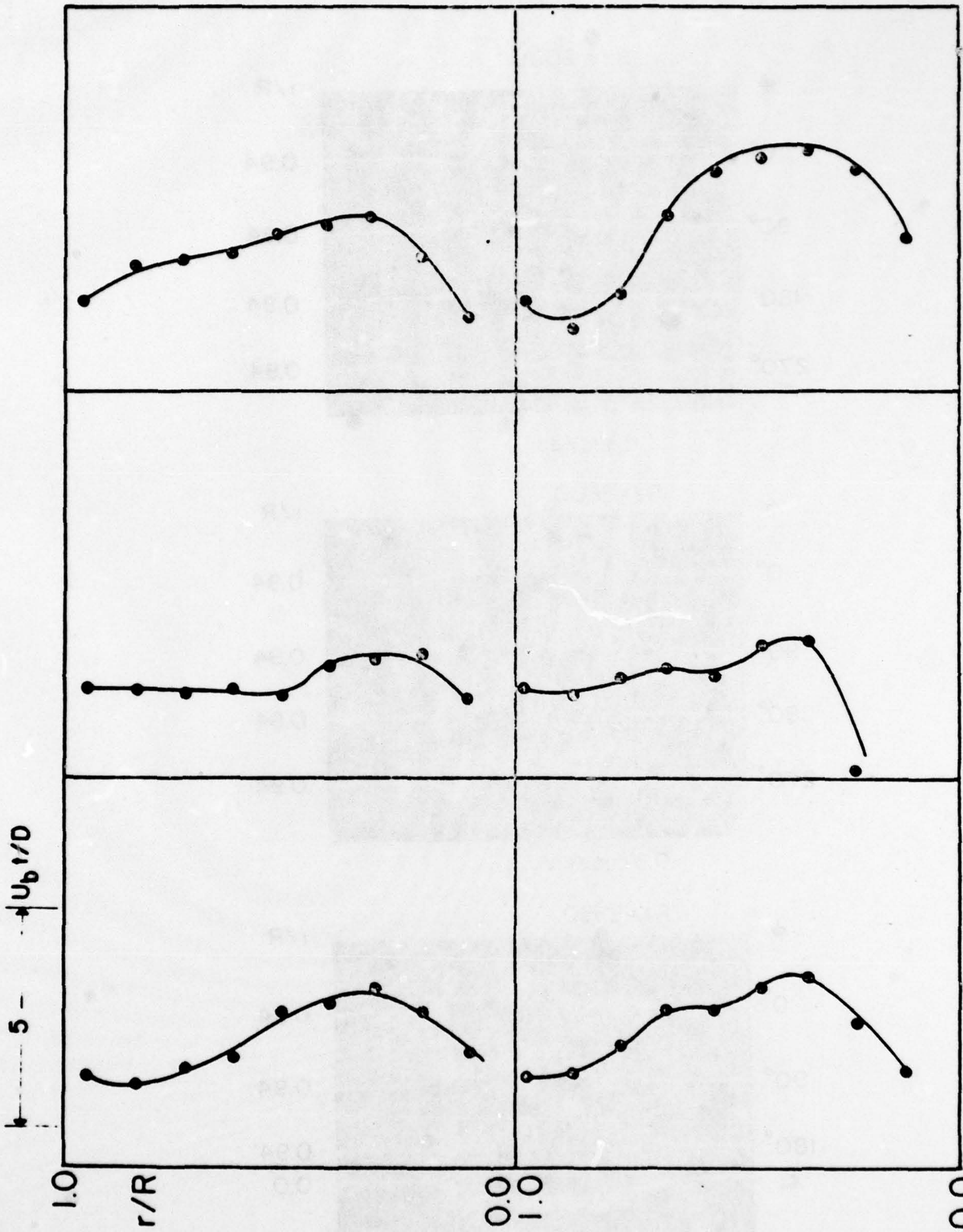


START 100
END 440
GAP = 10
ΔT = 40 ms
1.0
r/R
0.0
1.0
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34

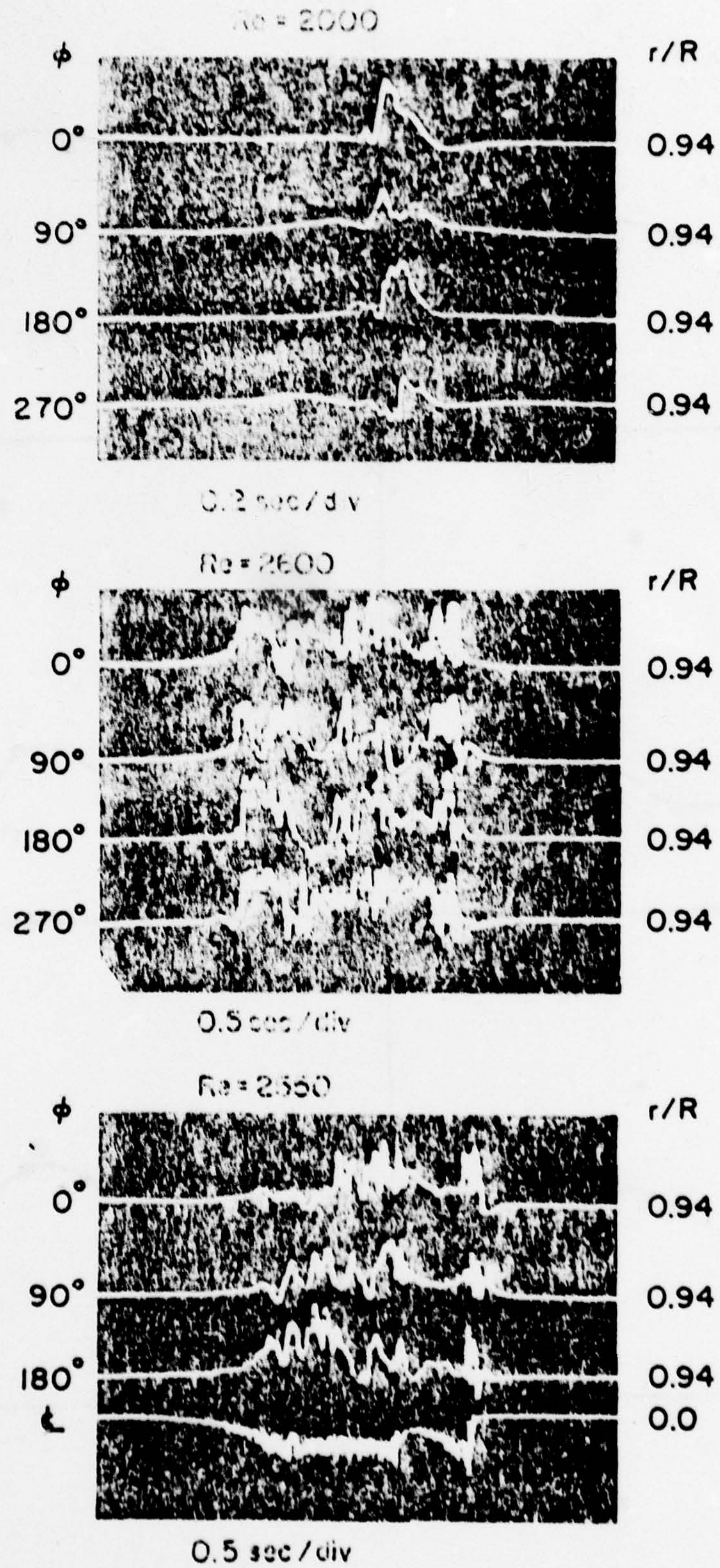

START 120 GAP = 2 ΔT = 5 ms
END 188
1.0
r/R
0.0
1.0
0.0
3
4
5
6
7
8
9


30
20
10
0
$U_b t/D$
r/R
0.0
0.13
0.25
0.36
0.48
0.60
0.72
0.84
0.96
170
200


START 200
END 370
GAP = 5
ΔT = 20ms
1.0
r/R
0.0
1.0
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34



U_b'/D
5
1.0
r/R
0.0
1.0
0.0
0.0


Re = 2000
φ
r/R
0°
0.94
90°
0.94
180°
0.94
270°
0.94
0.2 sec/div
Re = 2600
φ
r/R
0°
0.94
90°
0.94
180°
0.94
270°
0.94
0.5 sec/div
Re = 2550
φ
r/R
0°
0.94
90°
0.94
180°
0.94
℄
0.0
0.5 sec/div

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TRANSITION
PIPE FLOW
PUFF AND SLUGS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Fully developed Poiseuille flow in a pipe was artificially disturbed at $x/D = 400$ and $17<Re<4000$. Puffs and slugs generated by the disturbance were identical to the structures observed when the flow in the inlet region had undergone transition (Wygnanski and Champagne 1973). Since the disturbance was sufficiently strong to cause transition even at low Reynolds numbers the appearance of either puffs or slugs depended on the Reynolds number only. Velocity measurements in the pipe were taken with rakes of hot wires using digital acquisition methods and in this way each realization could be observed in its entirety. The coherence of the

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large structures was studied in radial and azimuthal directions. Puffs and slugs generated by the disturbance were mapped and found to be identical to the structures observed at the inlet region of the pipe. It was established that a slug which has all the attributes of a fully developed turbulent pipe flow is generated by a coalescence of puffs. The puff, which seems to contain a small number of toroidal eddies appears to be a fundamental coherent structure in a fully developed turbulent pipe flow. Previous observations, which were based on a single-point measurement and ensemble-averaged data did not reveal the full structure of the puff in the same detail as the present techniques. Single realizations were analysed showing instantaneous velocity profiles, vorticity perturbation contours, as well as streamlines moving with the structure. Artificially generated succession of puffs which were allowed to interact, closely resembled a slug. The evolution of a slug from puffs was thus established.